EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms (2017)

Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.4277

Applying geomorphological principles and engineering science to develop a phased Sediment Management Plan for Mount St Helens, Washington

Paul Sclafani,[1] Chris Nygaard[1] and Colin Thorne[2*]
[1] Portland District, US Army Corps of Engineers, Portland, OR USA
[2] School of Geography, Nottingham University, Nottingham, UK

Received 29 April 2016; Revised 16 October 2017; Accepted 18 October 2017

*Correspondence to: Colin Thorne, School of Geography, Nottingham University, Nottingham, UK. E-mail: colin.thorne@nottingham.ac.uk

ESPL
Earth Surface Processes and Landforms

ABSTRACT: Thirty-seven years post-eruption, erosion of the debris avalanche at Mount St Helens continues to supply sediment to the Toutle–Cowlitz River system in quantities that have the potential to lower the Level of Protection (LoP) against flooding unacceptably, making this one of the most protracted gravel-bed river disasters to date. The Portland District, US Army Corps of Engineers (USACE) recently revised its long-term plan for sediment management (originally published in 1985), in order to maintain the LoP above the Congressionally-authorized level, while reducing impacts on fish currently listed under the Endangered Species Act, and minimizing the overall cost of managing sediment derived from erosion at Mount St Helens. In revising the plan, the USACE drew on evidence gained from sediment monitoring, modelling and uncertainty analysis, coupled with assessment of future LoP trends under a baseline scenario (continuation of the 1985 sediment management strategy) and feasible alternatives. They applied geomorphological principles and used engineering science to develop a phased Sediment Management Plan that allows for uncertainty concerning future sediment yields by implementing sediment management actions only as, and when, necessary. The phased plan makes best use of the potential to enhance the sediment trap efficiency and storage capacity of the existing Sediment Retention Structure (SRS) by incrementally raising its spillway and using novel hydraulic structures to build islands in the North Fork Toutle River (NFTR) and steepen the gradient of the sediment plain upstream of the structure. Dredging is held in reserve, to be performed only when necessary to react to unexpectedly high sedimentation events or when the utility of other measures has been expended. The engineering-geomorphic principles and many of the measures in the phased Sediment Management Plan are transferrable to other gravel-bed river disasters. The overriding message is that monitoring and adaptive management are crucial components of long-term sediment-disaster management, especially in volcanic landscapes where future sediment yields are characterized by uncertainty and natural variability. © 2017 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd.

KEYWORDS: disaster management; gravel-bed river; Mount St Helens; North Fork Toutle River; sediment management; volcanic eruption

Introduction

The catastrophic eruption of Mount St Helens (MSH) on 18 May 1980 altered the surrounding landscape both physically and ecologically (Swanson and Major, 2005), with the catchment of the North Fork Toutle River (NFTR) being the most severely affected (Lipman and Mullineaux, 1981; Janda *et al.*, 1984). Impacts were greatest in the upper basin of the NFTR, but affected the entire Toutle–Cowlitz drainage system and part of the Columbia River (Figure 1). In the years immediately following the 1980 eruption, erosion of material deposited during the event generated sediment loads that were two to three orders of magnitude greater than pre-eruption levels. Thirty-seven years later, the average annual sediment load input to the Toutle–Cowlitz drainage system is still about 10 times greater than it was prior to the eruption.

The principal, long-term risk posed to downstream communities by the persistently elevated sediment load stems from sedimentation in the lower Cowlitz River, which increases the probability of flooding in river-side communities including Castle Rock, Lexington, Kelso and Longview (Figure 1). Recognizing this, soon after the eruption the United States Congress authorized the Portland District, US Army Corps of Engineers (USACE) to manage sediment in the Toutle–Cowlitz system as necessary to ensure that the Level of Protection (LoP) provided by levees along the lower Cowlitz River is maintained at or above the value prescribed in the Congressional authorization throughout a 50-year period that began in 1985.

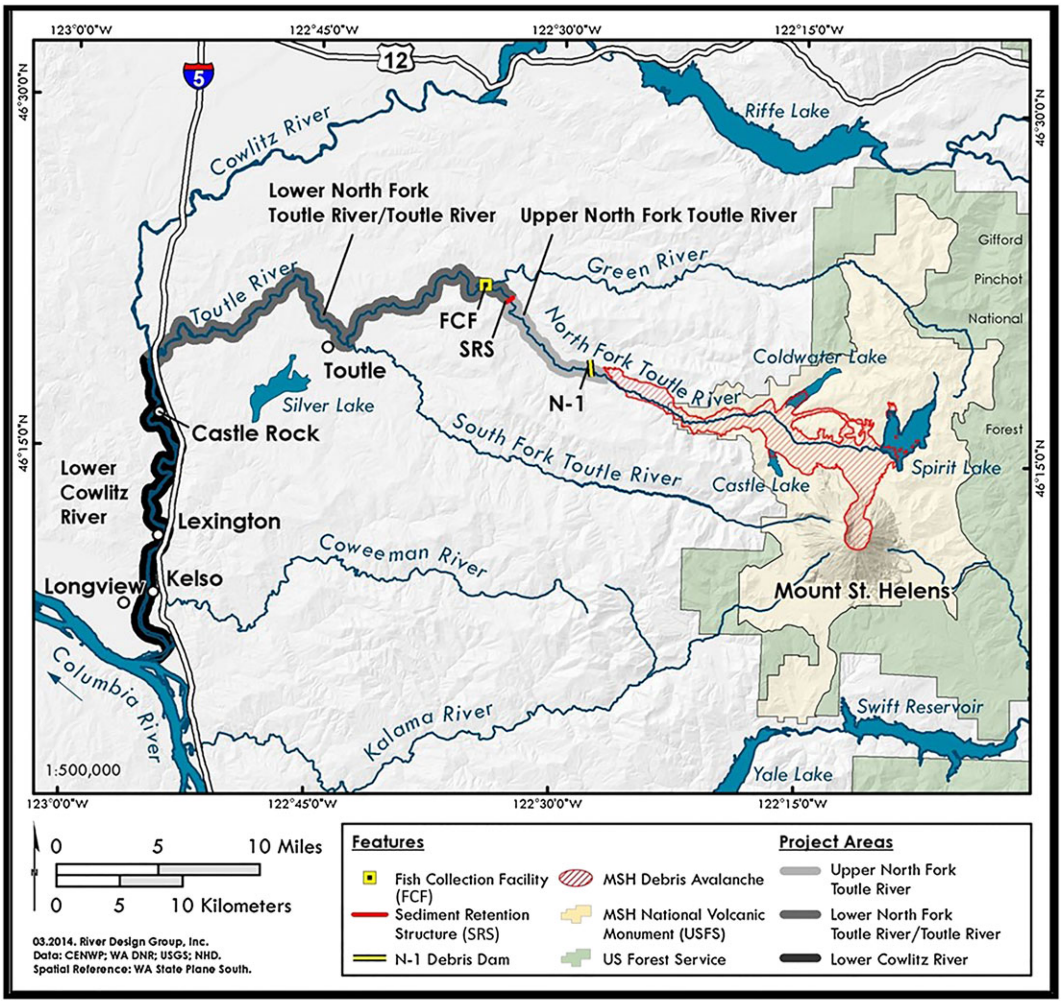

Figure 1. Location map showing Mount St Helens, the Toutle–Cowlitz drainage system extending to the Columbia River, the extent of the debris avalanche, lakes dammed by the debris avalanche, locations of the N-1 dam, Sediment Retention Structure (SRS) and Fish Capture Facility (FCF), and communities along the lower Cowlitz River that are at risk of flooding. Note that most of the debris avalanche itself lies within the Mount St Helens Volcanic Monument, which eliminates options for erosion and sediment source control. [Colour figure can be viewed at wileyonlinelibrary.com]

In responding to the eruption and elevated flood risks in the Toutle–Cowlitz system during the years immediately following the event, the USACE undertook emergency sediment management actions and conducted a series of rapid scientific and engineering studies, culminating in an original Sediment Management Plan (SMP) (USACE, 1983) and Decision Document (USACE 1985). Implementation of the original SMP was based on a series of feasibility studies and design memoranda published during the 1980s (USACE, 1984, 1986a, 1986b, 1987a, 1987b). The centrepiece of the original SMP was construction of the Sediment Retention Structure (SRS), which is an earth embankment across the NFTR approximately 22 km downstream of MSH (Figure 1). The SRS was completed in 1989 and it trapped more than three quarters of the sediment input from the upper NFTR until sediment accumulating in the sediment plain upstream of the structure reached the crest of the spillway, in March 1998.

By 2009, it had become apparent from the results of ongoing monitoring of annual sediment yields from the upper basin, sedimentation rates in the lower Cowlitz River and deteriorating trends in the LoP, that continuing with the original SMP was no longer feasible. Thus, further studies were conducted to update the geoscience and engineering knowledge bases for managing sediment in the Toutle–Cowlitz system, and then revise the original SMP. This paper reports how these more recent studies led to development and adoption of a revised SMP that uses phased and adaptive sediment management actions as needed to ensure that the LoP will exceed the Congressionally-authorized value up to and beyond 2035, despite persistence of annual sediment yields from upper NFTR that are elevated compared to pre-eruption levels, highly sensitive to the occurrence of floods, and unpredictably variable.

The Eruption and Sediment Management Responses (1980–2009)

The eruption and initial emergency responses (1980–1984)

At 08:32 on 18 May 1980 a magnitude 5 earthquake triggered a massive landslide comprised of three failure blocks on the northern flank of MSH (Figure 2) (Voight *et al.*, 1981; Glicken, 1996). Seconds later, a lateral volcanic blast and ground-hugging pyroclastic flow followed the landslide, devastating a 600 km^2 area to the north of the mountain and blanketing it with tephra (Hoblitt *et al.*, 1981; Voight *et al.*, 1981; Waitt *et al.*, 1981). A thick layer of volcanic ash was then deposited over a wide area and a series of lahars and floods redistributed some of the debris from the eruption along the valleys of the Toutle and Cowlitz Rivers, extending as far downstream as the Columbia River (Figure 1). In the months and years

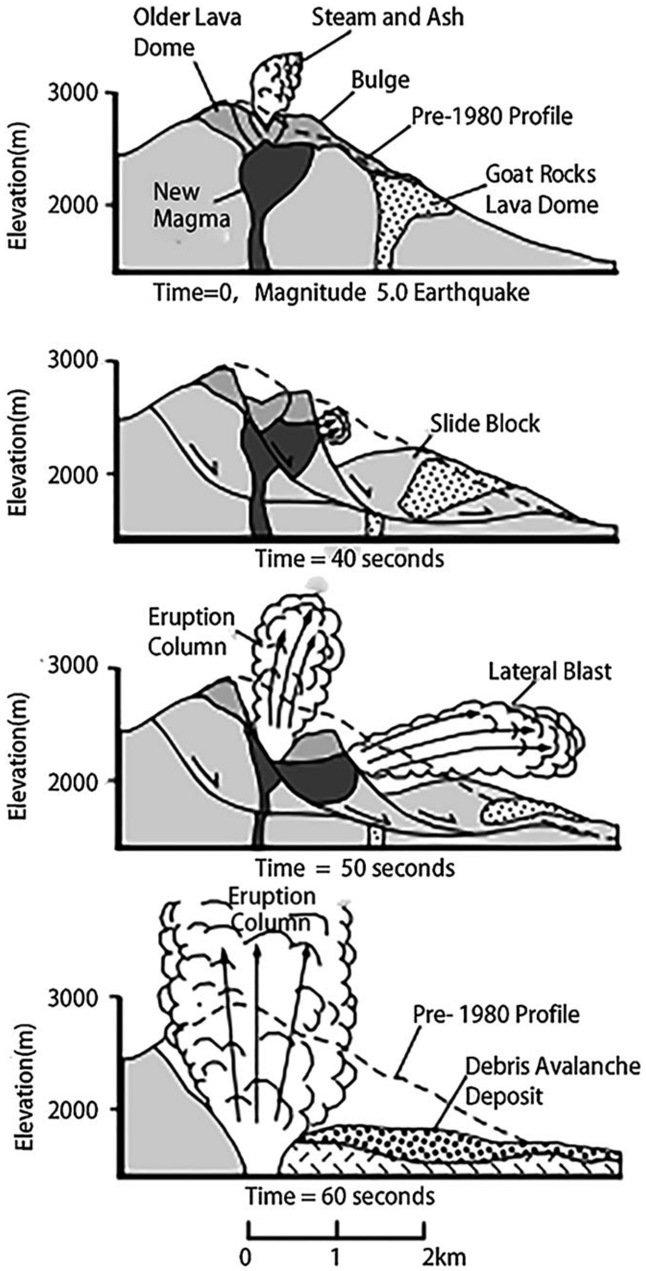

Figure 2. Sequence of events during the first minute of the eruption on 18 May 1980. (A) pre-eruption condition, (B) massive, three-block landslide, (C) lateral blast and pyroclastic flow, (D) debris avalanche burying upper course of North Fork Toutle River (NFTR) to a maximum depth of 140 m. Note: Following the initial event a layer of ash was deposited over the area around the volcano, and lahars and shallow-water floods redistributed debris avalanche and pyroclastic flow sediments downstream through the Toutle–Cowlitz system as far as the Columbia River (see Figure 1) (courtesy of USGS Cascades Volcano Observatory).

following the eruption, fluvial processes and more lahars eroded sediment from the devastated area at enormous rates, depositing it in the Toutle, Cowlitz, and Columbia Rivers.

During the eruption, the upstream 27.4 km of the NFTR were buried to an average depth of about 40 m by a layered deposit referred to as the debris avalanche. This wedge-shaped deposit has a volume of about 2.5 km^3 and comprises (from top to bottom) of layers of: volcanic ash (fine-grained, highly erodible, generally up to 3 m thick, but in places as much as 11 m); pyroclastic flow material (mostly fine-grained but with up to 20% gravel, low-density, highly erodible, generally up to 11 m thick but as much as 49 m thick close to the mountain on the pumice plain); landslide deposits (ranging from fine-grained sediment to massive boulders, much less erodible than either ash or pyroclastic flow material, up to 140 m thick close to the mountain) (Glicken, 1996).

The initial influx of sediment from the eruption reduced the discharge capacities of the channels of the Toutle and Cowlitz Rivers (Schuster, 1983), putting the communities of Toutle, Castle Rock, Lexington, Kelso, and Longview (Figure 1) at significant risk of flooding, even during normal flows. Sedimentation also continued to pose a serious navigation hazard in the Columbia River. In response, a range of emergency measures was immediately implemented by the Portland District, USACE (Willingham, 2005). These measures included:

- construction of debris dams across the North and South Forks of the Toutle River (the site of the N-1 dam on the NFTR is indicated in Figure 1) to reduce the volume of sediment being delivered to the Toutle River;
- raising of levee crest elevations at vulnerable locations along the lower Cowlitz River between Castle Rock and Longview (Figure 1);
- dredging of the Columbia River around the mouth of the lower Cowlitz to eliminate the navigation hazard (Schuster, 1983);
- dredging of the Toutle–Cowlitz drainage system that removed ~5.7 million m^3 of sediment from these rivers, between December 1980 and May 1981 alone.

The N-1 dam had already filled with sediment when it was damaged by a lahar and then decommissioned, in 1982 (Simon, 1999) and sedimentation persisted in the lower Toutle River, with an additional ~2.3 million m^3 being dredged during the winter 1982–1983. When a further ~3.4 million m^3 of sediment had to be dredged from around the confluence of the Toutle and Cowlitz Rivers during the winter 1983–1984, it was apparent that continued dredging alone would not provide a long-term solution to managing sediment in the Toutle–Cowlitz system.

The original sediment management plan (SMP) (1985)

When it was recognized that elevated sediment yields from the upper NFTR were likely to persist for decades, the Portland District began work on a long-term SMP, which was issued as the 'Decision Document' in 1985 (USACE, 1985). Learning from the short life of the small N-1 sediment dam on the NFTR, the central component of the 1985 Plan was a much larger SRS located at a suitable site 22 km downstream of MSH (Figure 1). The SRS is an earth embankment (crest length = 575 m, height = 55 m) with a roller-compacted, concrete upstream face and a design sediment storage capacity of ~200 million m^3 (Figure 3). The intention was for the SRS to trap and retain sediment throughout the remainder of the 50-year period for which the USACE was authorized to manage sediment at MSH. Construction began in 1987 and the SRS was completed in 1989.

The 1985 SMP also specified further improvements to levees along the lower Cowlitz River and made provision for the dredging to be continued during construction of the SRS and resumed when, at a future but unspecified date, sediment accumulating upstream of the SRS blocked the pipes releasing water through the structure, diverting it instead over the spillway and causing the SRS's trap efficiency to decrease as a result (USACE, 1985).

Figure 3. Sediment Retention Structure (SRS) and sediment plain in winter 2012–2013 (following implementation of the first spillway raise, in summer, 2012) (courtesy of USGS Cascades Volcano Observatory). [Colour figure can be viewed at wileyonlinelibrary.com]

Sediment management under the original SMP (1985–2008)

During the 1990s, the SRS trapped 75 to 95% of the sediment eroded from the debris avalanche (Figure 4), but accumulating sediment progressively buried the structure's outlet pipes and during the 1996 flood water passed over the spillway for the first time. In March 1998 sediment accumulating upstream of the SRS reached the elevation of the spillway (Major *et al.*, 2009) and the structure's trap efficiency gradually decreased, falling from over 75% during the 1990s to about 30 to 40% during the early-2000s (Figure 4). This allowed more sediment to pass downstream into the Toutle–Cowlitz system and renewed sedimentation in the lower Cowlitz River was documented, especially during and following a spike in sediment transport in the NFTR that was related to the geomorphological impacts of a flood in 2006 that triggered a channel avulsion in Loowit Creek – a headwater stream that switched from draining into Spirit Lake to become a tributary to the NFTR (Figures 5 and 6; Simon and Klimetz, 2012).

Following the 2006 flood, a marked loss of conveyance capacity caused at least in part by the influx of avulsion-related sediment to the lower Cowlitz triggered actions necessary to maintain the authorized LoP. These actions included renewed dredging and additional local levee improvements. Although these measures were successful in preventing the LoP from falling below its Congressionally-authorized value, the low trap efficiency of the SRS observed between 2002 and 2008 (Figure 4) and challenges posed by continued dredging of the lower Cowlitz River indicated that the LoP for some communities along the lower Cowlitz might fall below the authorized level as early as 2018 unless further sediment management actions were undertaken.

Review of the original SMP and sediment expert workshop (2009)

Although the 1985 SMP recognized that dredging in the Cowlitz River would be required after the outlet pipes were blocked and the SRS became a 'run-of-river' structure, by the time dredging actually became necessary in the mid-2000s it had become both more expensive and more difficult to permit than originally envisaged. Furthermore, listing under the Endangered Species Act (ESA) of fish populations inhabiting

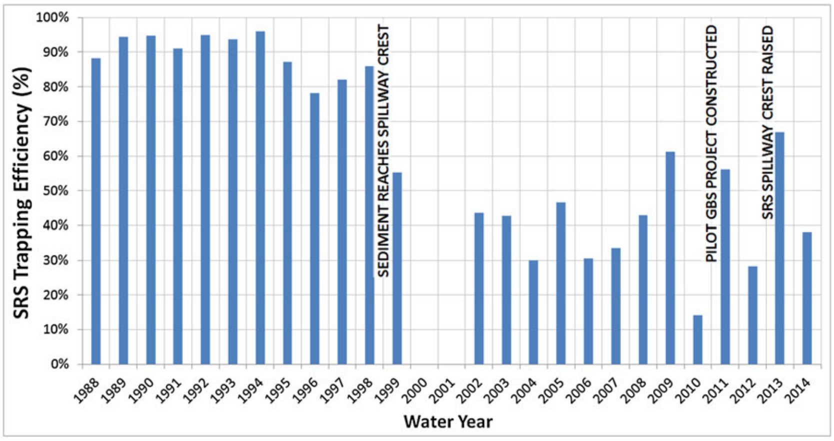

Figure 4. Record of changes in the trap efficiency of the Sediment Retention Structure (SRS) in relation to key events including sediment stored upstream reaching the original spillway crest (March 1998), construction of the Grade Building Structure (GBS) pilot project (summer 2010) and implementation of the pilot spillway raise (summer 2012). [Colour figure can be viewed at wileyonlinelibrary.com]

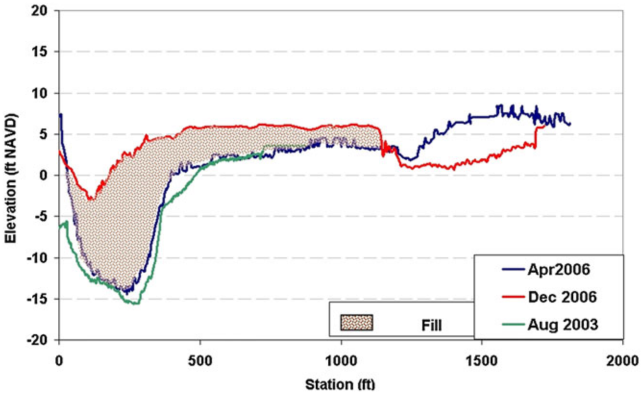

Figure 5. Sedimentation in the lower Cowlitz River related to the 2006 flood. Such deposition has the potential to rapidly and significantly reduce the Level of Protection (LoP) provided by the lower Cowlitz floodway and levee system. [Colour figure can be viewed at wileyonlinelibrary.com]

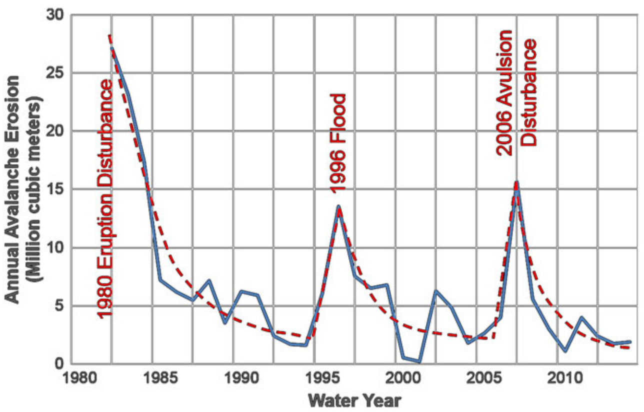

Figure 6. Annual sediment yields to the Sediment Retention Structure (SRS). The 1996 and 2006 floods can be seen to interrupt the longer-term decline in sediment yields, indicating that the fluvial system remains sensitive to disturbance by flood events. The 1996 event was the flood of record. The 2006 flood had a return period of only ~20 years but generated a spike in sediment loads due to an avulsion in Loowit Creek – a headwater stream in the North Fork Toutle River (NFTR) basin. Note: This plot uses 'water years' that start on 1 October and end on 30 September. [Colour figure can be viewed at wileyonlinelibrary.com]

the Toutle–Cowlitz system [including chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*), chum salmon (*Oncorhynchus keta*), steelhead trout (*Oncorhynchus mykiss*), eulachon (*Thaleichthys pacificus*) and green sturgeon (*Acipenser medirostris*)] meant that opportunities for dredging were limited to a few weeks each year.

However, the original SMP anticipated the need for periodic re-evaluation of its components in response to changes in local conditions and legislative contexts, and specific provision was made for periodic updating and revision (USACE, 1985). Acting on this provision, in 2009 the Portland District initiated a review of the original SMP and organized a Sediment Expert Workshop to consider options for future sediment management. At the workshop, experts considered 16 options for sediment management having potential to help meet the authorized LoP through to 2035 and beyond, while improving conditions for fish and minimizing the overall cost of managing sediment (Table I). The outcomes of the 2009 workshop informed subsequent screening of these 16 potential sediment management options and revision of the 1985 SMP.

Monitoring, Modelling and Forecasting Sediment Yields (1982–2009)

Context

The 2009 workshop identified forecasting future trends in annual sediment yield as an issue to be addressed in revising the long-term plan for managing sediment in the Toutle–Cowlitz system. To address this, the Portland District compiled and reviewed all available data on sediment yields since the 1980 eruption, and then undertook numerical modelling to provide an engineering-forecast of future sediment yields suitable for sediment management planning purposes.

Initial estimates of the 50-year cumulative sediment yield (1983–1985)

Immediately post-eruption, sediment yields from the debris avalanche were truly monumental, and the USACE's initial estimate of the 50-year cumulative sediment yield being in excess of 750 million m^3 reflected this (USACE, 1983). During the next two years, a rapidly declining trend in annual sediment yield emerged and in 1985 the initial estimate was revised down to ~420 million m^3 (USACE, 1985). This estimate was based on the assumption that the rapid decline in annual sediment yield observed during the first few years following the eruption would continue, albeit at an exponentially decaying rate, as had been observed during geomorphic 'recovery' or 'relaxation' in other fluvial systems following disturbance (Graf, 1977). The revised estimate of the forecasted yield made in 1985 was the basis for selecting construction of a single, very large structure – the SRS – coupled with dredging of the lower Cowlitz as necessary, as the preferred option in the original SMP (USACE, 1985).

Sediment monitoring and interpretation (1985–2009)

The original SMP was formulated on the expectation that elevated sediment yields to the NFTR would decline through time and that sediment loads in the Toutle–Cowlitz system would be monitored and interpreted to make available the data needed to characterize sediment transport rates and trends (USACE, 1985). In this context, during the late-1990s, scientists at the US Geological Survey, Cascades Volcano Observatory (CVO) analysed post-eruption suspended sediment measurements in the Toutle River, together with USACE's records of sediment accumulation upstream of the SRS since its completion in 1989. CVO's scientists then used the combined data to construct a synthetic time series of annual sediment loads at the US Geological Survey (USGS) Kid Valley gauge (located just downstream from the SRS) between 1982 and 1998 (Major *et al*., 2000). Based on these data and records from other fluvial systems disturbed by volcanic activity Major *et al*. (2000, p. 822) noted that:

> Sediment yields in the aftermath of explosive volcanic eruptions typically decline nonlinearly as physical and vegetative controls diminish sediment supply. However, spatial and temporal perturbations resulting from hydrologic functions are likely to punctuate, or even temporarily reverse, long-term trends, which complicates projection of time to equilibrium.

Table I. Three-level screening of option for sediment management (USACE, 2010)

Measures	Status after first screening	Status after second screening	Status after third screening (Limited Re-evaluation Report, LRR)
1. Debris avalanche stabilization	Not viable – treatment would soon be scoured and avalanche is mostly within the Mount St Helens (MSH) National Volcanic Monument		
2. Elk Rock sediment dam	Not viable – would store significant sediment but much more costly than raising the Sediment Retention Structure (SRS)		
3. Grade Building Structures (GBSs)	Viable – some sediment storage; low cost and environment impact	Viable	Viable – pilot project proves GBS feasibility
4. Sump in sediment plain	Not viable – due to high cost and limited sediment trapping and storage potential	Re-introduced in response in third screening in response to public comment	Not viable – further analysis shows this to be very costly and ineffective
5. Raise SRS dam and spillway	Viable – relatively high cost but significant sediment trapping and storage potential	Viable	Viable – but very high cost suggests measure #6 is a better option
6. Incremental raising of SRS spillway	Not viable – moderate sediment impact for low cost but concerns exist regarding capacity of SRS to convey Probable Maximum Flood (PMF) (which is a debris flow)		Viable – because updated PMF models show that debris flows do not reach the SRS
7. Bank stabilization (including lower Toutle-1 dredge spoil site, LT-1)	Not viable – bank erosion not a significant source of sediment. However, local bank treatment at LT-1 dredge spoil disposal site be considered	Re-introduced in third screening in response to public comment	Not viable – input of sediment from erosion at LT-1 small compared to the sediment budget for Toutle–Cowlitz system
8. Sump at lower Toutle dredge spoil site (LT-1)	Viable – further assessment of sediment trap efficiency required to test feasibility in phase 3	Viable	Not viable – costly and limited capacity to trap sand sized sediment that deposits in lower Cowlitz River
9. Expand floodplain of Toutle River	Not viable – limited opportunities to expand the floodplain and limited sediment impact		
10. Modify operation of Mossyrock Dam	Viable – recommend additional evaluation of potential to pass/flush sediment through lower Cowlitz River	Viable – reliability of approach unproven but still worth considering	Not viable – limited and unreliable for passing/flushing sediment through lower Cowlitz
11. Levee improvements	Not viable – would increase flood risk in non-leveed reaches. Minor improvements still appropriate though		
12. Cowlitz River dredging	Viable – effective but costly plus environmentally sensitive	Viable – effective but with environmental and disposal issues	Viable – but need to limit frequency and extent
13. Expand floodplain of lower Cowlitz	Viable – further consideration warranted	Not viable – due to extent of floodplain development and infrastructure, plus cost of removing contaminated soils	
14. Horseshoe bend sump or cutoff in lower Cowlitz River	Not viable – limited benefit for major cost plus potential for finding contaminated soils		
15. Reconnect old channel at mouth of Cowlitz River	Not viable – limited benefit for major cost plus potential for finding contaminated soils		
16. Dikes to flush sediment at mouth of Cowlitz River	Viable – further consideration warranted	Viable	Not viable – some benefit but strongly rejected due to impacts on listed fish and wildlife

Note: The first, second and third screenings correspond to initial, feasibility-level and practicality-level evaluations.

In interpreting the implications for sediment management, they concluded that:

> ... yields from basins that experience dominantly channel disturbances will likely remain elevated for as much as several decades. Thus, measures designed to mitigate sediment transport in the aftermath of severe explosive eruptions must remain functional for decades, p. 822.

We now know that elevated sediment yields in the NFTR have indeed persisted, primarily due to post-disturbance channel evolution characterized by geomorphically complex response (Schumm, 1977). Such response involves cycles of incision, aggradation and widening, with channel changes becoming increasingly dependent on the occurrence of floods due to the combined effects of slope adjustments, bed armouring/fining, bank instability, and lateral channel erosion (Simon and Thorne, 1996; Major *et al.*, 2000; Zheng *et al.*, 2013, Zheng *et al.*, 2017). In this context, Major *et al.* (2000) correctly predicted that:

> If bank instability persists, high sediment yield persists.

WEST Consultants (2002) performed further analysis of the combined USGS and USACE sediment records. They coupled the river hydrograph with a one-dimensional sediment transport model (HEC-RAS; Brunner, 2001) to characterize the decreasing trend in annual sediment yields observed between 1982 and 1999. They concluded that this trend had the form of an exponential decay curve with the equation:

$$y = 21.2\ x^{0.6}$$

where y is the annual sediment input to the sediment plain upstream of the SRS (in t/yr) and x is the time elapsed since the eruption (in years). Based on extrapolating their best fit line to 2035, WEST Consultants (2002) recommended further downward revision of the 50-year, cumulative sediment yield to ~310 to ~320 million m^3.

Notwithstanding this, Major (2004) used his calculation that two decades of erosion following the eruption had removed only ~12% of the sediment deposited in the debris avalanche to support a further cautionary statement to the effect that:

> Persistent extraordinary suspended sediment yields from severely disturbed channels indicate that mobile supplies of sediment remain accessible, and those supplies will not be exhausted for many more years or possibly decades.

Biedenharn group engineering study (2008–2009)

Biedenharn Group (2010) provided support for the hypothesis that decay in sediment yields from the debris avalanche might be slower than initially thought. Their study calculated erosion by differencing digital elevation models (DEMs) representing parts of the upper NFTR basin on various dates between 1984 and 2007. These DEMs were derived from conventional surveys conducted in the years immediately following the eruption and a subsequent series of aerial LiDAR (light detection and ranging) surveys. It should be noted that most of these DEMs provide only partial coverage of the debris avalanche. To support long-term sediment management planning, the Biedenharn Group (2010) adopted a conservative assumption that the decreasing trend in annual sediment yields observed immediately following the eruption actually ended during the late-1980s. Their characterization of the trend in cumulative erosion between 1990 and 2007 consequently had the form of a straight line with the equation:

$y = 4.5\ x$.where y is the cumulative erosion (in U.S. tons) and x is the calendar year since the eruption. Based on this linear relationship, the Biedenharn Group (2010) provided a conservative engineering estimate of the 50-year cumulative sediment yield of ~560 million m^3.

Post-2009 Expert Workshop Studies and Pilot Projects (2009–2012)

USDA-ARS study (2009–2011)

Following review of the available data and contrasting forecasts for future sediment yields at the Sediment Expert Workshop in 2009, a new study was commissioned by the Portland District to establish the potential for further decay in future sediment yields from the debris avalanche. This study, undertaken by staff at the US Department of Agriculture, Agricultural Research Service (USDA-ARS) National Sedimentation Laboratory at Oxford, Mississippi, coupled re-surveys of 30 of the USGS-monumented cross-sections in the upper NFTR drainage system with advanced modelling of bank and terrace slope instability using the Bank Stability and Toe Erosion Model (BSTEM) (Simon *et al.*, 2011).

In the USDA-ARS study, Simon and Klimetz (2012) used data derived from long-term monitoring performed by the CVO (for a summary, see Mosbrucker *et al.*, 2015) together with additional data they collected themselves to concur with the conclusion reached by CVO scientists that, post-2000, bank erosion had become the dominant source of sediment delivered to the SRS. They also highlighted the growing significance of floods, citing as evidence channel changes/avulsions in headwater tributaries like Loowit Creek, and spikes in annual sediment yields observed during and following the floods of February 1996 and, particularly, November 2006 (Figure 6).

Notwithstanding flood-related disturbances to the long-term, declining trend, Simon and Klimetz (2012) forecast that, unless the fluvial system were to be perturbed by further volcanic activity, long-term sediment yields to the SRS should be expected to decay logarithmically according to the function:

$$y = 69.3\ \ln(x) + 53.7$$

where y is the annual sediment yield (in tons) and x is the time elapsed since the eruption (in years), indicating a 50-year cumulative sediment yield of ~330 million m^3

Grade building structure pilot project (2010–monitoring is ongoing)

The 2009 Sediment Expert Workshop considered 16 measures that could theoretically be taken to manage sediment in the Toutle–Cowlitz system (Table I). Following post-workshop screening in 2010, the Portland District took the decision to test the efficacy of Option #3 in Table I: construction of grade building structures to retain additional sediment on the sediment plain upstream of the SRS. A cutoff berm, cross-valley step-weir and baffle structure, and 14 Engineered Log Jams (ELJs) were installed upstream of the SRS in a pilot project intended to establish their potential to increase the gradient of the sediment plain and induce the formation of vegetated islands (Figure 7).

Figure 7. Grade building structures installed in the 2010 Pilot Project. Inset orthophoto shows (a) cutoff berm, (b) cross-valley step-weir and baffle structure, and (c) island building structures. Main picture shows Engineered Log Jam island building structures in area outlined in red in the orthophoto three years after their installation. [Colour figure can be viewed at wileyonlinelibrary.com]

Monitoring and performance appraisal of the pilot project continues and will do so until the structures are, in due course, buried by sediment accumulating upstream of the SRS.

Pilot spillway crest raise (2012)

When constructed (between 1987 and 1989), the SRS was fitted with a spillway of sufficient capacity to protect the earth embankment against over-topping during the Probable Maximum Flood (PMF). At that time, the PMF was not envisaged to be a conventional water flood, but rather a debris flow caused by breaching of the debris-avalanche dam impounding Castle Lake (Figure 1). The spillway was therefore sized to safely pass such a debris flow (USACE, 1990). In 2010–2011, PMF models were updated to reflect changes to the geometry of the NFTR valley caused by sediment accumulation upstream of the SRS (USACE, 2011b; Denlinger, 2012). Four scenarios were modelled: two simulating water floods from different breaching modes of the Castle Lake debris-avalanche dam, the third simulating a debris flow caused by breaching of debris-avalanche dam at Castle Lake, and the fourth simulating a debris flow originating from the crater of MSH. The results indicate that the probable maximum debris flow emanating from either the crater or Castle Lake would not reach the SRS spillway due to the width of the valley of the upper NFTR and the breadth of the sediment plain upstream of the SRS (USACE, 2011b; Denlinger, 2012). A water flood resulting from a 'worst case scenario' breaching of Castle Lake would produce a peak flow of 40 000 m^3/s but this would be attenuated to just 6000 m^3/s by the time it reached the SRS. This discharge is much lower than the original design flood for the spillway. The high degree of attenuation is again attributed to the great width of the upper valley and breadth of the sediment plain. These outcomes led to downward revision of the PMF (USACE, 2012) which, in turn, allowed raising the crest elevation of the SRS spillway without compromising its safety, as a management option.

The efficacy of raising the spillway in reducing sedimentation in the lower Cowlitz was tested in the summer of 2012 (USACE, 2013). The spillway was raised by ~2.3 m, using a design that did not steepen it or adversely affect downstream migration by juvenile, anadromous fish or the potential for future re-establishment of volitional passage upstream by returning adults (Figure 8). Subsequent sediment monitoring shows raising the spillway restored the trap efficiency of the SRS to over 60% (Figure 4), and bathymetric surveys in the lower Cowlitz River indicate that sedimentation that began when the SRS began operating as a 'run-of-river' structure in March 1998 has been reversed (Figure 9).

USACE Forecast of Future Annual Sediment Yields (2012)

Modelling approach and outcome

In light of continuing uncertainty in sediment yield predictions (USACE, 2009), the Portland District decided to undertake further modelling to develop a 'Future Expected Deposition Scenario' (FEDS) (USACE, 2011a). To ensure that sediment yield forecasts were conservative, it was assumed that there would be no significant decrease in the average annual rate of erosion of the debris avalanche during the period up to 2035.

In forecasting future sediment yields to the SRS, the Portland District compiled as complete a time-series of measured discharges and estimated sediment yields as possible for the period between March 1998 (when the SRS became a 'run-of-river' structure) and 2007, based on their own records plus those of the CVO and the USDA-ARS. They then used a Monte-Carlo approach to synthesize multiple time-series of possible annual sediment yields, starting in 2008 and ending in 2035.

Thousands of possible annual sediment yield and downstream deposition series were generated, creating a spectrum of possible sediment futures that was statistically stable. A single, simulated time-series representing the median fluvial future in terms of both future average annual discharges and sediment yields was then designated as the 'FEDS'. The selected time-series has a distribution of floods and sediment yield events similar to those observed between 1990 and 2007 (Figure 10). This similarity indicates that events in the time

Figure 8. Pilot raise of the Sediment Retention Structure (SRS) spillway under construction during summer 2012. [Colour figure can be viewed at wileyonlinelibrary.com]

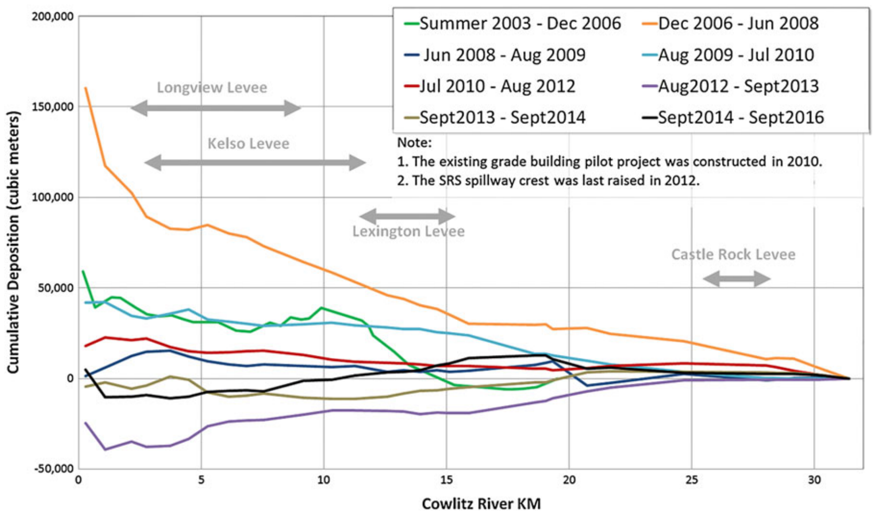

Figure 9. Rates of cumulative sedimentation in the lower Cowlitz River between 2003 and 2013. The impacts of various measures can be discerned. The 2010 Grade Building Structure pilot project slows deposition (compare deposition between August 2009 and July 2010 to that between July 2010 and August 2012), and the 2012 spillway raise reverses sediment deposition in the lower Cowlitz River (i.e. cumulative erosion observed between August 2012 and September 2014). [Colour figure can be viewed at wileyonlinelibrary.com]

series are representative of floods actually experienced in the Toutle–Cowlitz system. Based on the median fluvial future, and solely for the purpose of long-term sediment management planning, the Portland District USACE developed an engineering estimate of ~130 million m^3 for the cumulative sediment yield from erosion of the debris avalanche during the period between 2008 and 2035.

Although the Portland District's 'FEDS' makes no allowance for climate change, a subsequent study (Meadows, 2014) considers a range of possible hydroclimatic future scenarios for the upper NFTR catchment, derived from a database compiled by the Columbia Basin Climate Change Scenarios Project (CBCCSP) (Hamlet *et al.*, 2010, 2013; Tohver *et al.* 2014). Under this range of possible hydroclimatic futures, the cellular-automata landscape evolution model CAESAR-LisFlood (Coulthard *et al.*, 2013) was used to forecast long-term sediment yields up to 2100 and beyond. Long-term future average annual sediment yields forecast using CAESAR-LisFlood range between ~2.5 and ~4.5 million m^3/yr (Meadows 2014; Figure 10), resulting in a forecast that the cumulative sediment yield in 2035 is likely to be between 200 and 300 million m^3. This range reflects uncertainty regarding the effects of climate change and natural variability, while also allowing for model uncertainty.

Recognizing uncertainty and natural variability in future sediment yields

Considerable uncertainty remains regarding future sediment yields to the SRS (Figure 10). It must be accepted that this uncertainty is, to a degree, irreducible. Also, inter-annual variability in sediment yields is apparent in the historical record and this must be expected to continue. However, it also remains uncertain how the sensitivity of sediment yields to

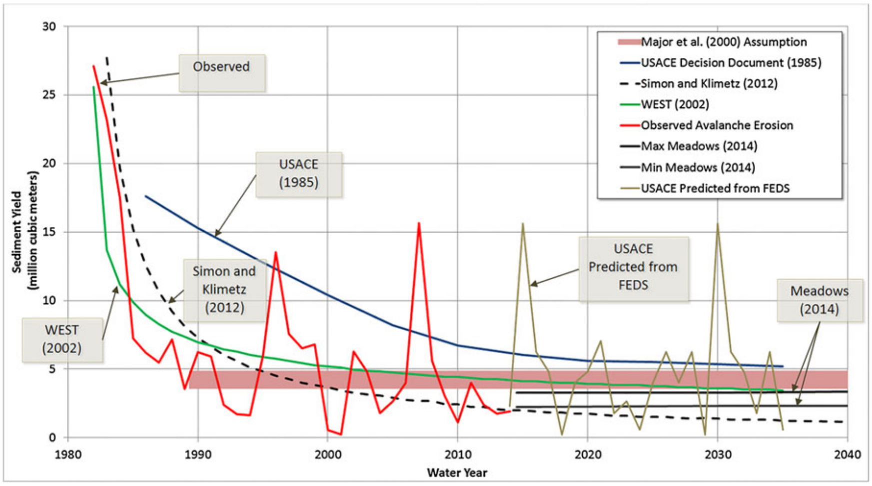

Figure 10. Observed sediment yields from the debris avalanche up to 2014 and predicted in the 'Future Expected Deposition Scenario' (FEDS) modelled by the Portland District (USACE, 2011a), together with long-term trends in sediment yields forecast in various studies. [Colour figure can be viewed at wileyonlinelibrary.com]

the occurrence of floods will evolve in future, and the timing and frequency of future events is simply unknowable. Therefore, it is impossible to predict when and how often spikes in sediment delivery to the lower Cowlitz River (like those observed in 1996 and 2006) will generate abrupt declines in the LoP that may trigger the need for emergency dredging.

Thus, the best practical response to managing uncertainty and natural variability in sedimentation events in the lower Cowlitz is to adopt an *adaptive approach* to long-term sediment management. This is not only desirable environmentally, it is also beneficial economically. Applying an overly conservative assumption (for example that floods will be frequent and sediment yields commensurately high), results in over-investment in building new sediment management infrastructure that probably is not needed. Conversely, assuming that future sediment yields will decline significantly may necessitate later implementation of emergency actions that are both costly and environmentally damaging. In contrast, an adaptable approach not only delays capital expenditure on new works until they are actually needed, but also avoids that expenditure altogether if future sediment yields are lower than forecast and late-stage components in the SMP prove unnecessary.

Revising the Long-term SMP

Options appraisal

Having identified options for sediment management and forecast future annual sediment yields, the Portland District turned its attention to revising the 1985 SMP (USACE, 2014). This process was addressed in three phases. In a first screening of options identified at the 2009 Expert Workshop (Table I), teams composed of USACE staff and regional stakeholders (including staff from other Federal and State agencies, officials from Cowlitz County and members of the communities affected) assessed their viability with respect to:

- significantly reducing flood risk to communities along the lower Cowlitz River;
- cost-effectiveness;
- adverse environmental/ecological impacts (including those on listed species);
- reliability of design;
- adaptability to changing conditions;
- protection of cultural resources;
- public acceptability.

Initial screening ruled out nine options, mainly due to shortcomings relating to reliability of design; cost-effectiveness; and capacity to significantly reduce flood risks (Table I). Full details of the first screening can be found in USACE (2010).

A second screening performed on the seven remaining potential options involved:

- production of conceptual designs;
- limited hydrologic, hydraulic, and sediment transport modelling;
- development of refined cost estimates.

The second screening eliminated option #13 (Table I). Appendix A of USACE (2010) fully explains the analyses performed for each option considered in the second screening.

The third screening evaluated the practical feasibility of the remaining six options, plus two that had been screened out in phase 2 but which were reconsidered in response to public comments and representations (options #4 and #7 in Table I), and #6, which was reintroduced because revised PMF models showed that debris flows would no longer reach the SRS.

The four options that remained after the third screening were:

#3: install further grade building structures (GBSs) on the sediment plain upstream of the SRS.
#5: raise the elevation of the SRS (including its spillway).
#6: raise the elevation of the SRS spillway, but not the embankment itself.
#12: dredge the lower Cowlitz River.

These four options were grouped into three (numbered) action alternatives for revising the long-term SMP:

1. Rely solely on dredging the lower Cowlitz River (option #12).
2. Raise the elevation of the SRS dam and spillway (options #5 and #6).
3. Phased implementation of GBSs, spillway raises, and dredging as and when necessary (options #3, #6 and #12).

These action alternatives were then evaluated in the Limited Re-evaluation Report (LRR) (USACE, 2014) with respect to:

- effectiveness in maintaining the authorized LoP in the lower Cowlitz;
- whole life cost (i.e. capital and maintenance costs averaged over the 18-year period between implementation of the revised plan in 2017 and 2035);
- environmental/ecological impacts (including those on listed species);
- reliability of design and operation;
- adaptability and potential for phased construction/implementation.

Appraisal of the three action alternatives (Table II) established action alternative 3 – phased implementation of spillway crest raise, GBSs, and dredging, as the best action alternative.

Preferred action alternative

In 2014, the Portland District indicated in its draft long-term sediment management planning document that phased implementation of options #3, #6 and #12 had been provisionally selected as the preferred action alternative for maintaining the authorized LoP in the lower Cowlitz River, and the relevant Environmental Impact Statement was issued the following year (USACE, 2015).

In the order in which they would be implemented, these options are:

#6: Raise the spillway of the SRS by up to 7.3 m in two further increments (neither involving an elevation rise greater than 4 m) as and when sediment stored upstream of the SRS reaches the current elevation of the spillway (which was raised by 2.3 m in the 2012 pilot project).

#3: Following each of the two remaining spillway raises, if and when sediment again reaches the spillway crest, construct further GBSs to retain additional sediment upstream on the sediment plain.

#12: Dredge the lower Cowlitz River on an 'as needed' basis. Dredging may be needed, for example, in response to rapid accretion during and following an event that generates a short-term spike in sedimentation or after the SRS again becomes a 'run-of-river' structure but no further spillway raises are possible and construction of additional GBSs cannot be justified.

These options are to be implemented only as and when needed, which conserves adaptive capacity during the life of the project, delays the costs and impacts of necessary actions, and avoids the costs and impacts of actions that turn out to be unnecessary. By selecting phased implementation as the preferred action alternative, USACE accepted that monitoring of hydrologic and sediment conditions at the SRS and in the lower Cowlitz is essential for reliable decision-making.

The maximum cumulative increase in spillway crest elevation is limited to 7.3 m owing to the need to safely pass the PMF. Also, engineering constructability dictates that future raises are best performed in two stages. Notwithstanding these constraints, the timings of the remaining incremental spillway raises are not prescribed *a priori*, and optimum partitioning of the 7.3 m raise between the two increments need not be identified until such time as conditions trigger the next raise. Adaptive capacity allows flexibility in decision-making, and allows construction to be synchronized with the funding cycle for sediment management actions.

Each time sediment reaches the spillway crest and sedimentation in the lower Cowlitz threatens to lower the LoP below its authorized value, a sediment management action (e.g. construction of further GBSs on the sediment plain) may be triggered. However, the phased plan recognizes that by the time this happens sediment yields to the SRS may have diminished sufficiently that further management actions are unnecessary.

However, if elevated sediment yields have not diminished sufficiently, and the LoP deteriorates as a result of reduced SRS trap efficiency, this will trigger construction of further GBSs on the sediment plain. The effectiveness of a cross-valley step-weir and baffle structure (intended to store sediment) and 14 ELJs (intended to induce island formation) in building up the grade of the sediment plain was tested at the prototype scale in the 2010 GBS Pilot Project (Figure 7). The island-building structures currently continue to perform as designed, prompting the genesis and growth of islands that divide the flow and promote proto-floodplains that are colonized by pioneering vegetation, roughen the sediment plain, reduce the sediment transport capacity of the NFTR and, hence, build up the gradient of the sediment plain. Conversely, scour immediately downstream of the 2010 cross-valley structure has prompted research into an alternative design that would train the NFTR into a 'serpentine' (i.e. tortuously meandering) course (Ettema *et al*., 2016).

If serpentine river training structures are implemented, the NFTR will flow around the structures at its natural gradient, so that the structures would not inhibit fish passage. Also, narrow gaps between the cross-valley structures and the valley sides would protect existing 'wall-base' channels at the edges of the sediment plain. Wall-base channels are important to salmon recovery in the Pacific Northwest because they have been shown to support both up and downstream passage while also providing excellent rearing habitat for juvenile fish (Peterson and Reid, 1984; Cederholm and Scarlett, 1991).

The 'serpentine' approach has recently been tested at 'proof of concept' level in a physical scale-model at Colorado State University (Figure 11) and the results are encouraging (Ettema *et al*., 2016). If the serpentine approach to building grade in the sediment plain is adopted, the Portland District will further evaluate, refine and optimize design of the necessary training structures prior to implementation.

Based on the conservative, engineering forecasts of future average annual sediment yields assembled by the USACE in the 'FEDS' (Figure 10), two further spillway raises, coupled with construction of further GBSs when the SRS again operates as a 'run-of-river' structure, are expected to maintain the LoP for communities along the lower Cowlitz at values higher than those Congressionally-authorized, at least up to 2035 and probably beyond that date.

Nevertheless, it is still possible that sedimentation could significantly reduce the LoP in the lower Cowlitz prior to 2035. Acute sedimentation may occur during and following a flood that generates an unusually high input of sediment to the Toutle–Cowlitz system, as experienced in 1996 and 2006 (Figures 5 and 6). Renewed capital dredging in the lower Cowlitz River is therefore retained as an option to deal with such events, which are forecast to be relatively infrequent. Furthermore, should future annual sediment yields turn out to be significantly higher than forecast, it is conceivable that the volume of sediment by passing the SRS and settling in the lower Cowlitz may cause the LoP for some of the communities to approach authorized values before 2035. In this unlikely scenario, the option remains to renew maintenance dredging late in the project. The extent of reaches requiring dredging would be limited to problematic shoals and bars, and the volumes of sediment removed would be much smaller than would have been the case for the 'Dredging Only' alternative

Table II. Evaluation of action alternatives in the Limited Re-evaluation Report (USACE, 2014)

Criteria	Action alternatives		
	1 Cowlitz River dredging only	2 Sediment Retention Structure (SRS) dam and spillway raise	3 Phased implementation of (spillway raises + Grade Building Structure (GBS) + dredging as needed)
Effective at maintaining Level of Protection (LoP)	Meets need	Meets need	Meets need
Economics – average annual cost (over 18 years 2017–2035)	Highest cost alternative.	High upfront costs but low out-year costs.	Least-cost alternative. Implementation costs distributed over time, dredging costs incurred only in responding to acute sediment deposition and may not actually be required.
Environmental considerations	Repeated, frequent impacts to habitats and species in river and also in potential spoil disposal areas.	Adverse impacts on upstream tributaries/habitats. Future upstream fish passage at the SRS unlikely to remain an option.	Upstream tributary habitat impacts and intermittent impacts in lower Cowlitz during dredging. Future volitional upstream fish passage at SRS remains an option.
Reliability	Reliable if dredging can be performed within constraints on environmental impact, disposal, and budget.	Reliable provided that monitoring is continued.	Reliable provided that monitoring and phased implementation are continued.
Adaptability	High adaptive capacity provided dredging of lower Cowlitz can be expanded – if required to meet by the LoP.	No adaptive capacity: requires full funding and construction upfront (which may be unnecessarily conservative).	Optimum adaptability: components of plan implemented over time and only as and when needed.

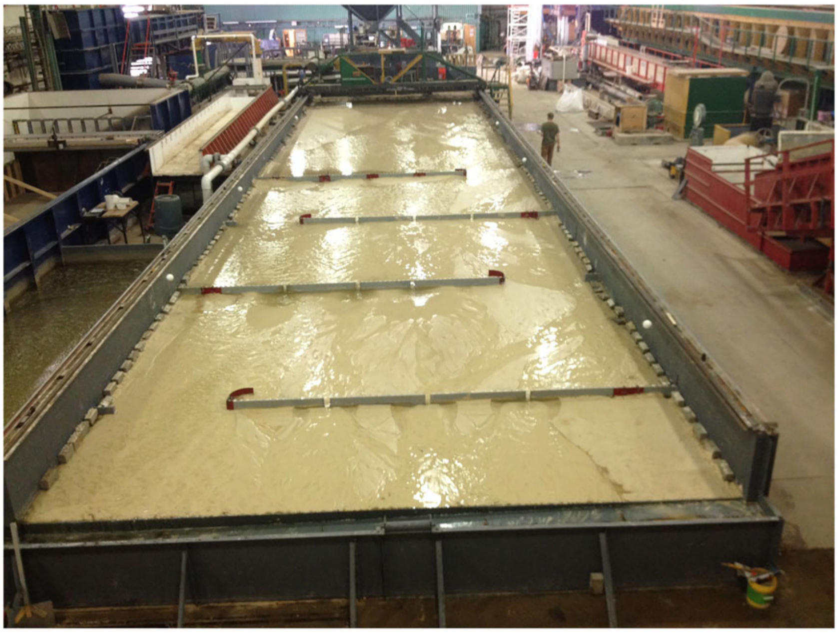

Figure 11. Physical model built at Colorado State University to perform 'proof of concept' experiments using a series of cross-valley structures to promote aggradation and build up the gradient of the sediment plain by training the braided channel of the North Fork Toutle River (NFTR) into a 'serpentine' course (Ettema *et al.*, 2016). [Colour figure can be viewed at wileyonlinelibrary.com]

(i.e. action alternative 1, in Table II). In both acute and chronic scenarios for problematic sedimentation, dredging would be performed only 'as needed' to maintain the LoP above the authorized value.

Delivering the Revised SMP in Practice

Overview

Delivering the phased plan in ways that are economically, socially and environmentally acceptable, and which use the Plan's adaptive capacity to best advantage, require a sound understanding of sediment dynamics within the Toutle–Cowlitz system and, particularly, the complex relationships between changes in the quantity of sediment passing the SRS, morphological responses in the Toutle–Cowlitz system downstream, and trends in the LoP. To foster this improved understanding, the results of on-going monitoring of sediment yields from the debris avalanche, channel changes in the Toutle–Cowlitz drainage network and trends in LoP are synthesized to inform decision-making.

The phased plan responds to and relies on accurate knowledge and assessment of trends in the LoP and identification of the appropriate sediment management action needed to prevent a breach of the authorized LoP. Given the lead time required for engineering implementation of structural measures, a further requirement is that monitoring of trends in the LoP triggers responses early enough to ensure that there is time for any action implemented to be effective in preventing the LoP from falling below its authorized value.

In applying the phased plan in practice, it must be borne in mind that the Portland District's management planning horizon is limited to a 50-year period that began in 1985. Thus, the USACE has no authority to plan or perform sediment management actions that may be necessary to maintain the current LoP beyond this planning horizon. But the District understands and takes seriously cautions from sediment experts that elevated sediment yields from the debris avalanche may persist for many decades (e.g. Major *et al.*, 2000; Meadows, 2014; Zheng *et al.*, 2017). The phased SMP therefore includes provision for further re-assessment in 2025 that will draw on the results of on-going monitoring to elucidate the processes responsible for trends in annual sediment yields, identify long-term trends in those yields, and re-evaluate the hazard posed by sedimentation rates in the lower Cowlitz River in light of the remaining sediment storage potential of the SRS. Monitoring, re-assessment and adaptation will ensure that the phased plan continues to meet the needs of communities along the lower Cowlitz River throughout the period of Congressional authorization, and into the foreseeable future.

Monitoring of the LoP

The primary goal of the phased plan is to ensure that communities at risk of flooding receive at least the LoP authorized by Congress. The foundation for achieving this goal is careful monitoring of the lower Cowlitz River floodway and levee system to support a Management Decision Support Framework (MDSF) that draws on the answers to the following questions:

1 Is the LoP currently being met?
2 Is there a declining trend in the LoP?
3 Is the current assessment being made within five-years of the end of the authorized period for sediment management, in 2035?

Depending on whether the answers to these questions are positive or negative, the MDSF considers the need for implementation of a sediment management action via one of three links (Figure 12).

Identifying the need for a sediment management action

The decision to implement a sediment management action is triggered if the authorized LoP is not being met and there is no reasonable expectation that it will recover without a new sediment management action, or if there is reason to believe

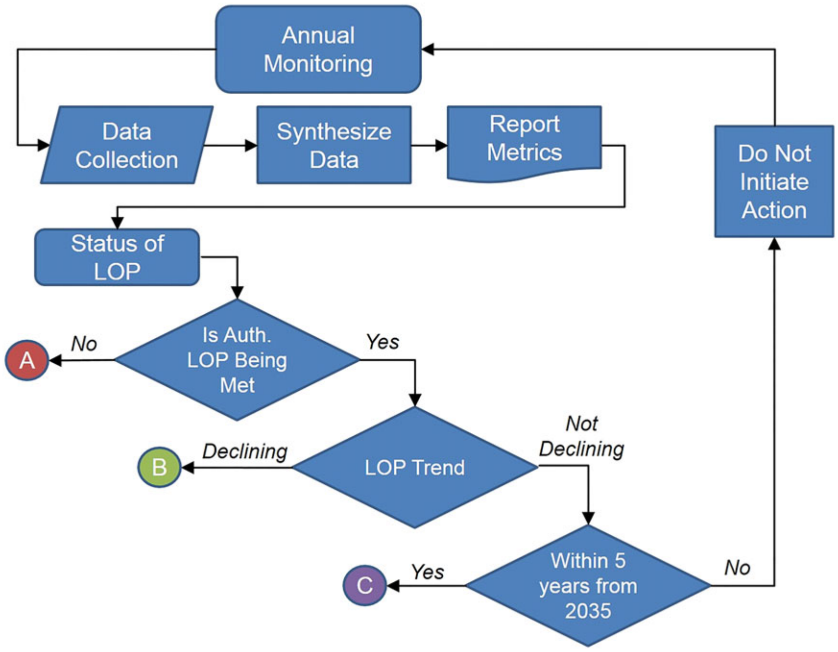

Figure 12. Management Decision Support Framework (MDSF) Step 1. This step considers whether the authorized Level of Protection (LoP) is being met, whether there is a declining trend in the LoP and whether the period for which the Portland District USACE is authorized to manage sediment in the North Fork Toutle River (NFTR) is within five-years of completion. Outcomes A (Red), B (Green) and C (Purple) lead to the matching, colour-coded questions in Step 2 (Figure 13). [Colour figure can be viewed at wileyonlinelibrary.com]

that the LoP will fall below the authorized value prior to 2035 unless action is taken to prevent this (Figure 13).

In situations where the LoP is declining, or the authorized LoP is not being met, the state of the sediment management system is assessed to predict whether the declining trend in the LoP is likely to reverse or the sub-authorized LoP is likely to recover to an acceptable value in the near future. For example, if a negative trend in LoP is detected following a major sediment transporting event, that negative trend probably reflects a flood-related spike in the sediment load input to the lower Cowlitz River. In that case, it is reasonable to expect the downward trend to cease or reverse once the sediment wave passes through to the Columbia River and, therefore, no new sediment management action is triggered. Conversely, if there is reason to expect that the LoP will not stabilize or recover, and the authorized period is more than five-years from completion, implementation of a new sediment management measure is triggered (Figure 13).

If annual monitoring detects a precipitous fall in the LoP, or if the LoP is forecast to fall below the authorized value within two or three years, a pre-emptive sediment management action is triggered. It is triggered because uncertainties concerning future floods, sediment loads, and budget/construction lead times require prudent action even though the LoP may still exceed the authorized value. Justification for the investment required to support such precautionary sediment management

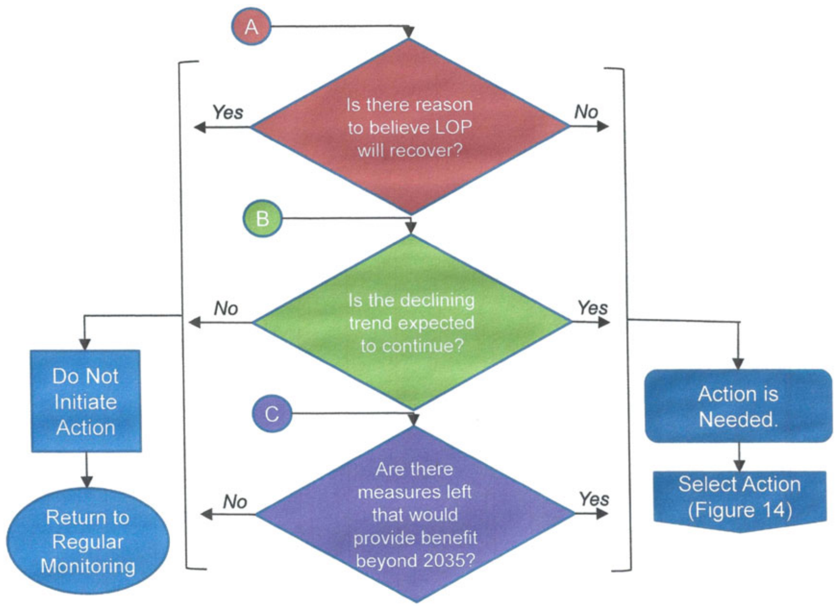

Figure 13. Management Decision Support Framework (MDSF) Step 2. This step indicates to the river engineers and scientists responsible for managing sediment in the Toutle–Cowlitz system whether a sediment management action should be triggered or deferred. [Colour figure can be viewed at wileyonlinelibrary.com]

actions rests not only on close monitoring of the LoP and sedimentation in the lower Cowlitz River, but also on regular surveys of the sediment plain to evaluate the trap efficiency of the SRS.

During the final five years of the authorized period, the need for pre-emptive sediment management actions necessary to provide sediment storage at the SRS beyond 2035 will be evaluated. If post-2035 sedimentation appears likely to be problematic, then an action may be triggered between 2030 and 2035 even though it is not actually needed to maintain the LoP during the authorized period.

Selection of the appropriate sediment management action

Once the MDSF has triggered an action (Figure 13), it is necessary to select and implement the sediment management option appropriate to the situation. This decision is made in the third step of the MDSF, which offers three options: raising the SRS spillway, constructing further GBSs on the sediment plain, or dredging critical reaches in the lower Cowlitz River (Figure 14).

In deciding which sediment management option to implement, it is essential to match the action to the current situation in the Toutle–Cowlitz sediment transfer system. For example, if a wave of sediment (generated by a flood event or resulting from sediment dynamics in the NFTR) is migrating through the lower Toutle River, then raising the spillway or building new GBSs on the sediment plain cannot prevent a decline in the LoP. In this instance, if action is needed, the only viable option is to dredge reaches of the lower Cowlitz floodway where the LoP is at, or is trending towards, its authorized value. Conversely, if cumulative deposition in the lower Cowlitz over a period of years is driving a declining trend in LoP, consideration is first given to an incremental raise of the SRS spillway, if such a raise is possible (Figure 8). If it is not, consideration is given to construction of ELJs and river training structures (Figures 7 and 11) to further increase the sediment storage capacity of the SRS.

A decision to dredge in response to chronic, cumulative sedimentation in the lower Cowlitz will be considered only when the potential for trapping and storing additional sediment upstream of the SRS has been fully exploited. Based on current forecasts of future sediment yields from the debris avalanche, this situation is unlikely to occur prior to 2035 – that is, within the period authorized for sediment management actions.

Discussion and Conclusions

Rivers draining catchments on the flanks of live volcanoes such as Mount Pinatubo and Mount Merapi are responsible for some of the most deadly and enduring gravel-bed river disasters (Gran *et al.*, 2011; De Bélizal *et al.*, 2013). Managing volcano-related sediment problems consequently presents pressing challenges to river scientists and engineers charged with protecting life and property in communities located in volcanic landscapes and at risk of flooding, erosion or sedimentation.

These challenges are compounded by large uncertainties inherent to predicting long-term trends in future sediment yields from landscapes and rivers disturbed by volcanic eruptions, which feature elevated sediment loads, heightened morphological-sensitivity to flood events and exaggerated variability in annual sediment yields from basins containing massive amounts of highly erodible, volcanically-derived sediment (Pierson and Major, 2014).

The reality is that plans and actions taken to manage long-term, sediment-related flood risks following an eruption must cope with irreducible uncertainties (i.e. uncertainties that cannot be made significantly smaller using better science) and amplified natural variability that cannot be predicted, in sediment futures that are, essentially, unknowable. This contrasts markedly to other sediment-management contexts and authorizations, where planning and implementation take

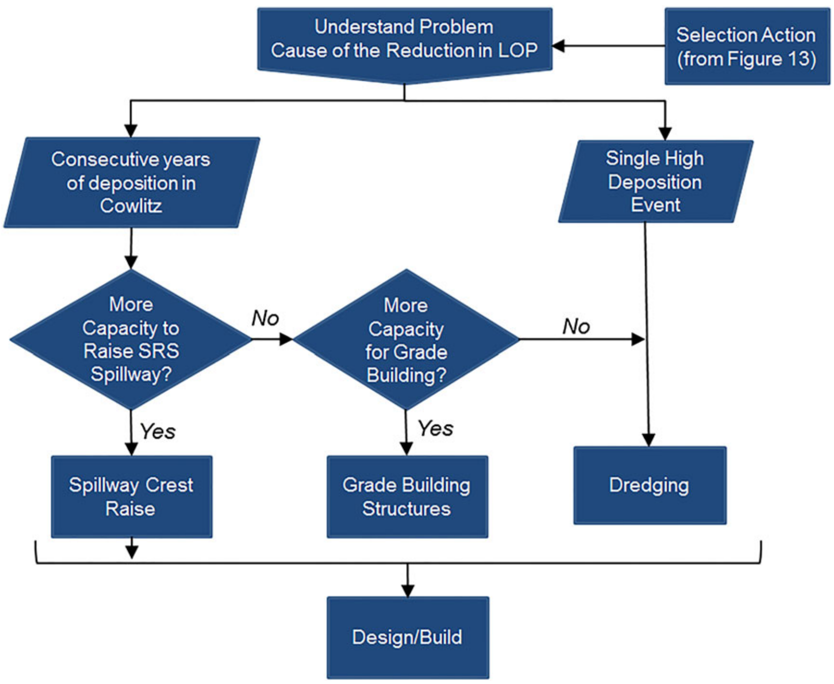

Figure 14. Management Decision Support Framework (MDSF) Step 3. This set guides decision-makers with respect to the appropriate sediment management action on the basis of the wider context for the need for action and the options available. [Colour figure can be viewed at wileyonlinelibrary.com]

place in response to circumstances that are well-described, with hydrologic and sediment parameters that are stationary, at least in the near to medium-term.

The original SMP for the Toutle–Cowlitz River system draining MSH, Washington (USACE, 1985) has been revised to formulate the current 'Phased Sediment Management Plan' (USACE, 2014, 2015). The Phased Plan is designed to accommodate uncertainty and natural variability by optimizing its adaptive capacity and metering-out deployment of that capacity over the period for which implementation of the Plan is authorized. The Phased Plan is capable of maintaining the authorized LoP afforded to communities along the lower Cowlitz River during the period for which the Portland District, USCAE is authorized to manage sediment in the Toutle–Cowlitz system, no matter how the future unfolds. It also minimizes costs by only implementing sediment management actions only as and when they are actually necessary, while applying a precautionary principle that ensures that the decision to trigger an action allows time not only for the measure to be designed and constructed, but also for it to begin working effectively. The Phased Plan is also designed to protect downstream fish passage and keep open the possibility of restoring volitional upstream passage in the future.

The adaptive, phased approach relies on monitoring and annual appraisal of:

- flood and other sediment-related risks;
- the basin-scale sediment transfer system;
- the condition and performance of existing flood and sediment infrastructure.

This is essential to inform river engineers and scientists responsible for deciding where and when to implement sediment management actions, as well as guiding selection of the option appropriate to address the particular sediment problem in the context of sediment dynamics in the wider fluvial system.

To this end, the 'Phased Sediment Management Plan' uses a three-part MDSF that prioritizes making best use of existing sediment-management infrastructure (especially the SRS), takes advantage of working with natural processes by building up the gradient of the valley floor (sediment plain) upstream of the SRS using GBSs, and reserves dredging as the management option of last resort, to be used only in emergencies (i.e. in response to acute sedimentation events driven by extreme floods) or after the potential of other options (SRS, GBS) has been fully exploited.

While the MDSF provides a structured and transparent basis for triggering management actions and selecting appropriate measures, it is not a substitute for sound professional judgment, which is indispensable to delivering disaster management that is prudent and safe. The reality is that decision-makers remain accountable for the decisions they make. That said, the Phased Plan employs geomorphic principles and engineering science to inform risk-based decision-making that is logical, cost-effective and explicable to stakeholders: it is difficult to overstate the importance of these attributes in an age of intense public accountability.

The underpinning geomorphological principles, engineering science and many of the features of the Phased SMP are transferrable to other gravel-bed river disasters. The over-riding message is that monitoring and adaptive management should be recognized as crucial to sustainable, long-term disaster management in gravel-bed rivers where future sediment yields are elevated, highly variable and characterized by great uncertainty.

Acknowledgements—The authors thank Dr Vern Manville and, especially, Dr Jon Major for their detailed, insightful and constructive comments on the first and second drafts of this paper, which benefitted both its content and clarity. In part, this work was supported by the Engineering and Physical Sciences Research Council, UK [grant number EP/P004180/1].

References

Biedenharn Group. 2010. *Toutle/Cowlitz River Sediment Budget*. Report prepared for the US Army Corps of Engineers, Portland District, Portland, OR. Biedenharn Group, LLC: Vicksburg, MS.

Brunner GW. 2001. *HEC-RAS River Analysis System: User's Manual*. US Army Corps of Engineers, Hydrologic Engineering Center: Davis, CA.

Cederholm CJ, Scarlett WJ. 1991. The beaded channel: a low-cost technique for enhancing winter habitat of Coho salmon. In *Fisheries Bioengineering Symposium: American Fisheries Society Symposium 10*. American Fisheries Society: Bethesda, MD; 104–108.

Coulthard TJ, Neal JC, Bates PD, Ramirez J, Almeida GA, Hancock GR. 2013. Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape evolution. *Earth Surface Processes and Landforms* **38**(15): 1897–1906.

De Bélizal E, Lavigne F, Hadmoko DS, Degeai JP, Dipayana GA, Mutaqin BW, Marfai MA, Coquet M, Le Mauff B, Robin AK, Vidal C. 2013. Rain-triggered lahars following the 2010 eruption of Merapi volcano, Indonesia: A major risk. *Journal of Volcanology and Geothermal Research* **261**: 330–347.

Denlinger RP. 2012. *Effects of Catastrophic Floods and Debris Flows on the Sediment Retention Structure, North Fork Toutle River, Washington*. Open File Report Number 2011–1317. US Geological Survey: Reston, VA.

Ettema R, Thornton CI, Armstrong D, Hughes SA, Abt SR. 2016. *Hydraulic Model Study of Grade-Building Structures for the North Fork Toutle River, Washington*. CSU-HYD Report No. 2016-1. Alden Research Laboratory, Inc. and Portland District, US Army Corps of Engineers, Colorado State University: Fort Collins, CO 184 pp.

Glicken H. 1996. *Rockslide-debris Avalanche of May 18, 1980, Mount St Helens Volcano, Washington*. Open File Report No. 96-677. US Geological Survey, Cascades Volcano Observatory: Vancouver, WA.

Graf WL. 1977. The rate law in fluvial geomorphology. *American Journal of Science* **277**(2): 178–191.

Gran KB, Montgomery DR, Halbur JC. 2011. Long-term elevated post-eruption sedimentation at Mount Pinatubo, Philippines. *Geology* **39**(4): 367–370.

Hamlet AF, Carrasco J, Deems J, Elsner MM, Kamstra T, Lee C, Lee S-Y, Mauger G, Salathe I, Tohver IM, Whitely BL. 2010. *Final Project Report for the Columbia Basin Climate Change Scenarios Project*. Climate Impact Group, University of Washington: Seattle, WA.

Hamlet AF, Elsner MM, Mauger G, Lee S-Y, Tohver IM. 2013. An overview of the Columbia Basin Climate Change Scenarios Project: approach, methods and summary of key results. *Atmosphere-Ocean* **51**(4): 392–415. https://doi.org/10.1080/07055900.2013.819555.

Hoblitt RP, Miller CD, Vallance JW. 1981. *Origin and Stratigraphy of the Deposit Produced by the May 18 Directed Blast*. US Geological Survey Professional Paper 1250. US Geological Survey: Reston, VA; 401–420.

Janda RJ, Meyer DF, Childers D. 1984. Sedimentation and geomorphic changes during and following the 1980–1983 eruptions of Mount St. Helens, Washington. *Shin Sabo* **37**(2): 10–21 **37**(3): 5–19.

Lipman PW, Mullineaux DR (eds). 1981. *The 1980 Eruptions of Mount St. Helens, Washington*. US Geological Survey Professional Paper 1250. US Geological Survey: Reston, VA.

Major JJ. 2004. Post eruption suspended sediment transport at Mount St. Helens: decadal-scale relationships with landscape adjustments and river discharges. *Journal of Geophysical Research* **109**(F1). https://doi.org/10.1029/2002JF000010.

Major JJ, Pierson TC, Dinehart RL, Costa JE. 2000. Sediment yield following severe volcanic disturbance – a two-decade perspective from Mount St. Helens. *Geology* **28**: 819–822.

Major JJ, Crisafulli CM, Frenzen P, Bishop J. 2009, After the disaster: the hydrogeomorphic, ecological, and biological responses to the 1980 eruption of Mount St. Helens, Washington. In Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest, O'Connor JE, Dorsey RJ, Madin IP (eds), Geological Society of America Field Guide 15. The Geological Society of America: Boulder, CO; 111–134. https://doi.org/10.1130/2009.fld015(06)

Meadows T. 2014. *Forecasting Long-term Sediment Yield from the Upper North Fork Toutle River, Mount St. Helens, USA*, PhD Thesis. School of Geography, University of Nottingham; 393 pp. http://eprints.nottingham.ac.uk/27800/1/Thesis_FINAL_TM.pdf

Mosbrucker AR, Spicer KR, Major JJ, Saunders DR, Christianson TS, Kingsbury CG. 2015. *Digital Database of Channel Cross-section Surveys, Mount St. Helens, Washington*. Open-file Report No. 951. US Geological Survey, Cascades Volcano Observatory: Vancouver, WA.

Peterson NP, Reid LM. 1984. Wall-base channels: their evolution, distribution, and use by juvenile coho salmon in the Clearwater River, Washington. *Proceedings of the Olympic Wild Fish Conference. Fisheries Technology Program, Peninsula College, Port Angeles, WA*; 215–225.

Pierson TC, Major JJ. 2014. Hydrogeomorphic effects of explosive volcanic eruptions on drainage basins. *Annual Review of Earth and Planetary Sciences* **42**: 469–507.

Schumm SA. 1977. *The Fluvial System*. John Wiley & Sons: Chichester; 338.

Schuster RL. 1983. Engineering aspects of the 1980 Mount St. Helens eruptions. *Environmental and Engineering Geoscience* **20**(2): 125–143.

Simon A. 1999. *Channel and Drainage-basin Response of the Toutle River System in the Aftermath of the 1980 Eruption of Mount St. Helens, Washington*. Open-file Report No. 96-633. US Geological Survey, Cascades Volcano Observatory: Vancouver, WA; 130.

Simon A, Klimetz D. 2012. *Analysis of Long-term Sediment Loadings from the Upper North Fork Toutle River System, Mount St. Helens, Washington*. Research Report No. 77. US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory: Oxford, MS.

Simon A, Thorne CR. 1996. Channel adjustment of an unstable coarse-grained stream: opposing trends of boundary and critical shear stress, and the applicability of extremal hypotheses. *Earth Surface Processes and Landforms* **21**(2): 155–180.

Simon A, Pollen-Bankhead N, Thomas RE. 2011. Development and application of a deterministic bank stability and toe erosion model for stream restoration. In *Stream Restoration in Dynamic Fluvial Systems*, Simon A, Bennett SJ, Castro JM (eds). AGU Geophysical Monograph Series. American Geophysical Union: Washington, DC; 453–474.

Swanson FJ, Major JJ. 2005. Physical events, environments, and geological—ecological interactions at Mount St. Helens: March 1980–2004. In *Ecological Responses to the 1980 Eruption of Mount St. Helens*. Springer: New York; 27–44.

Tohver IM, Hamlet AF, Lee SY. 2014. Impacts of 21st-century climate change on hydrologic extreme in the Pacific northwest region of North America. *Journal of the American Water Resources Association* **50**(6): 1461–1476.

US Army Corps of Engineers (USACE). 1983. *A Comprehensive Plan for Responding to the Long-term Threat Created by the Eruption of Mount St. Helens, Washington*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 1984. *Mount St. Helens, Washington Feasibility Report and Environmental Impact Statement, Toutle, Cowlitz and Columbia Rivers*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 1985. *Mount St. Helens, Washington Decision Document, Toutle, Cowlitz and Columbia Rivers*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 1986a. *Mount St. Helens, Washington, Toutle, Cowlitz and Columbia Rivers, Design Memorandum No. 3 (September)*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 1986b. *Mount St. Helens Sediment Control, Cowlitz and Toutle Rivers, Washington, Sediment Retention Structure Sediment Ranges, Design Memorandum No. 11 (December)*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 1987a. *Mount St. Helens Sediment Control, Cowlitz, and Toutle Rivers, Washington, Design Memorandum No. 10, Sediment Retention Structure Fish Collection Facility*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 1987b. *Mount St. Helens Washington, Toutle, Cowlitz and Columbia Rivers, Design Memorandum No. 15 (September): SRS Base-plus Dredging*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 1990. *Numerical Simulation of Mudflows from Hypothetical Failures of the Castle Lake Debris Blockage Near Mount St. Helens, WA: Final Project Report No. 90–05*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 2009. *Toutle/Cowlitz River Sediment Budget (October 2009)*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 2010. *Progress Report, Mount St. Helens Long-Term Sediment Management Plan for Flood Risk Reduction (June 2010)*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 2011a. *Mount St. Helens Future Expected Deposition Scenario (FEDS) (April 2011)*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 2011b. *Development of the PMF for the SRS (August 2011)*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 2012. *White Paper Describing Differences between 1985 and 2011 Probable Maximum Flood at the Sediment Retention Structure, North Fork Toutle River, WA*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 2013. *Mount St. Helens, Washington, Design Documentation Report No. 16 (June), Sediment Retention Structure 7-foot Spillway Raise*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 2014. *Limited Reevaluation Report: Mount St Helens Long-term Sediment Management Plan Update (Draft)*. Portland District, USACE: Portland, OR.

US Army Corps of Engineers (USACE). 2015. *Final Supplemental Environmental Impact Statement, Mount St. Helens Long-term Sediment Management Plan Update*. Portland District, USACE: Portland, OR.

Voight B, Glicken H, Janda RJ, Douglass PM. 1981. *Catastrophic Rockslide Avalanche of May 18*. US Geological Survey Professional Paper 1250. US Geological Survey: Reston, VA; 347–377.

Waitt RB, Hansen VL, Wood SH. 1981. Devastating pyroclastic density flow and attendant air fall of May 18—Stratigraphy and sedimentology of deposits. In *The 1980 Eruptions of Mount St. Helens, Washington*. US Geological Survey Professional Paper 1250. US Geological Survey: Reston, VA; 439–458.

Consultants WEST. 2002. *Mount St Helens engineering reanalysis. Hydrologic, hydraulic and sedimentation analysis. Volume 1*. Technical Report to the Portland District, USACE. WEST Hydraulic Consultants Inc.: Bellevue, WA.

Willingham WF. 2005. The Army Corps of Engineers' short-term response to the eruption of Mount St. Helens. *Oregon Historical Quarterly* **106**(2): 174–203.

Zheng S, Wu HY, Thorne CR, Simon A. 2013. Morphological evolution of the North Fork Toutle River following the eruption of Mount St. Helens, Washington. *Geomorphology* **208**: 102–116. https://doi.org/10.1016/j.geomorph.2013.11.018.

Zheng S, Thorne CR, Wu B, Han S. 2017. Application of the Stream Evolution Model to a Volcanically Disturbed River: The North Fork Toutle River, Washington State, USA. *River Research and Applications* **33**(6): 937–948.

